

DESIGN AND DEVELOPMENT OF FLIGHT CONTROL LAWS FOR LCA

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The design and development of the flight control laws for LCA was started in early 1993 with the formation of the National Control Law Team consisting of engineers and scientists drawn from five national aeronautical research and development institutions. The control laws being developed by this team are independently verified and validated by an IV and V team and the design process, specifications, data and results are also audited by specialists from British Aerospace UK.

The Light Combat Aircraft is a single engine, tail-less delta wing aircraft which is designed to be aerodynamically unstable in the longitudinal axis. In order to stabilise the airframe and achieve the desired performance over the entire flight envelope it incorporates a quad redundant full authority digital Fly By Wire (FBW) Flight Control System (FCS). The adoption of an unstable configuration with a delta wing having scheduled Leading Edge Slats (LES) has resulted in aerodynamic benefits especially at supersonic speeds. The use of automatically scheduled LES results in a reduction in drag for a given lift and increased manoeuvre margin for a given thrust i.e. for a given drag coefficient.

LCA is configured to be aerodynamically unstable in the pitch axis, the instability level depends on the flight condition (Mach No., altitude and angle of attack) and configuration (leading edge slat position, mass and c.g. location). The stability is artificially recovered by using feedback control. Processed pitch rate, normal acceleration, angle of attack and airspeed information along with pilot stick/trim inputs actively drive the elevons symmetrically. The stability and command augmentation system is configured to result in an Angle of Attack (α) / normal acceleration (nz) command system in the longitudinal axis.

The airframe is directionally stable except at high angles of attack (α). However, there is a need to further augment the directional stability and the Dutch roll damping (which is low for the unaugmented aircraft). The lateral and directional axes are coupled and the roll rate response shows significant Dutch roll oscillations. The two axes are decoupled from the roll stick input via the

control law. The aircraft is made to roll about the velocity vector in response to a roll stick input, to suppress the kinematic coupling between α and the sideslip angle β especially at high α . In addition, the β build-up during initiation of turns is minimised. The control law ensures a roll rate demand from the roll stick and a β demand from the rudder pedals. As the β build-up is minimised by the control law, the pilot need not operate the rudder pedals during turns. Due to inertial coupling between the pitch and the roll/yaw axes, the roll rate and sideslip demands are reduced during pitching manoeuvres. This is achieved in the control law through interconnects from the pitch axis to the roll and yaw axes.

Processed roll rate and lateral stick input drive the elevons differentially from the lateral axis. The rudder command is derived from processed angle of attack, roll rate, yaw rate, lateral acceleration, elevon commands, stick inputs and pilot rudder pedal demand.

In addition to recovering stability and providing the required modal characteristics (short period / phugoid / roll mode / Dutch roll) the control laws also improve the following characteristics of the closed loop system -

- i) performance robustness with respect to plant variations and external disturbances
good command following in a particular flight parameter (x / nz in the longitudinal axis, p and β in the lateral - directional axes)
- iii) stable crossover region with adequate phase and gain margins for the inner stabilisation and pilot loops
- iv) roll off the gains at high frequencies to reduce the sensitivity to sensor noise and high frequency aircraft model uncertainties including structural modes.

These important requirements are met by suitably shaping the frequency response of individual transfer functions using dynamic elements (phase advance, lag and lead filters) in addition to tuning the feedback / feed forward gains as a function of flight condition. The multiple requirements many of which are conflicting in nature

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are achieved by carefully tuning the controller parameters (dynamic elements / gains) in the feed forward / feedback paths. The feed forward path elements are designed to improve the handling qualities including resistance to pilot induced oscillations.

The other critical element is the design of the notch filters, which are introduced in series with the inertial feedback sensors to minimize the structural mode pickup and ensure adequate stability margins over the entire structural frequency range. These notch filters introduce phase lags at low frequencies and hence affect the rigid body stability margins. The structural mode amplitude characteristics of the aircraft are obtained experimentally by suspending the fully equipped airframe using rubber bungee cords in the structural coupling ground test rig. The surfaces are then dynamically excited over the complete frequency spectrum. The Structural Coupling Tests are done in two phases - one with the control loops open to map the airframe structural mode amplitudes as a function of frequency, and then later once the notch filters are designed and implemented in the DFCC the stability margins are experimentally measured by breaking the loops at the actuators. Finally all the feedback and command loops are closed and the surfaces excited to ensure that the structural modes are adequately suppressed over the entire frequency range.

The control law development process for the LCA has been planned in a progressive manner. For the initial flights of the TD-1 / TD-2, since angle of attack, sideslip and airdata (Pt, Ps) information was not available (pending flight calibration) to the control laws, they were operated in the fixed gain mode over a restricted flight envelope using only signals from the inertial sensors (rate gyros and accelerometers). In the second block of flights since the airdata and angle of attack sensors are flight calibrated, the fixed gain control laws will be replaced by the gain-scheduled version to progressively expand the flight envelope.

The full up control laws receive inputs from inertial sensors (roll, pitch, yaw rate gyros, normal and lateral accelerometers), pilot stick (pitch and roll LVDT's), rudder pedal (LVDT's), airdata probes (one nose and two side probes), and two AoA vanes. The total pressure (Pt) and static pressure (Ps) signals are primarily used for scheduling the controller gains and filter time constants, at low speeds these signals are also used to augment the speed stability / static margin. The control laws have automatic safeguards against loss of control and exceedance of structural limits (Boundary limiting / Carefree manoeuvring)

and also incorporate autopilot functions to minimize pilot workload.

To cater for AoA failures, the control laws incorporate a reversionary mode wherein an equivalent AoA signal is generated for feedback by processing total normal acceleration. To cater for an airdata system failure (two failures in either P_T or P_S), the control law has a fixed gain reversionary mode as an ultimate backup. In the event of an airdata system failure the gains are frozen at the last good value and the pilot can then manually switch over to the standby gains using a switch in the cockpit. There are two sets of fixed gains in the standby mode, which are automatically selected depending on the position of the undercarriage selection lever. These two sets of feedback gains have been so designed that irrespective of where the airdata failure occurs in the design flight envelope, the pilot is able to recover control of the aircraft by first flying with the frozen gains and then switching over to the appropriate standby gain set. These fixed gain control laws have already been successfully flight tested during the initial block of flights on LCA TD-1.

Figure I shows a schematic of the synthesis cycle used in the optimisation of the LCA control laws. A suite of control law design and performance evaluation tools has been developed to accomplish the linear design / trade off studies and arrive at an optimal design. In order to optimise the aircraft response under large pilot inputs and also to ensure aircraft safe operation under coupled inputs in the pitch, roll and yaw axes, a number of non-linear signal shaping elements are incorporated in the control law structure. These elements are optimised using extensive offline and real-time simulation based tools.

For LCA control law development two dedicated real time simulation platforms have been used. The Engineer-in-loop simulator ('ELS'), located at the National Aerospace Laboratories, has been primarily used as a control law 'Design' simulator and has been very successfully used as a rapid prototyping tool for LCA handling qualities optimisation. The 'ELS' simulator has also been used to develop and integrate to the six DoF simulation all the critical subsystem models of LCA such as primary actuator non-linear models, complex undercarriage models etc. The Real Time Simulator ('RTS'), located at the Aeronautical Development Establishment, has been used as the LCA handling qualities simulator for formal assessment of the LCA handling qualities by project test pilots.

Though the ground based simulation facilities have excellent visual cues, for certain phases of flight and high workload tasks like landing and close formation flying, motion cues play a significant role in the evaluation of the performance and hence the control laws have to be tested in actual flight. In-flight simulation (IFS) is a tool that allows assessment of the handling qualities "in flight" of a prototype aircraft without compromising flight safety. In IFS, the fly-by-wire host aircraft's variable stability flight control system is modified to behave dynamically like the test aircraft under evaluation. The control laws under test are implemented onboard the IFS computers and the modified aircraft plus flight control system is now flown by the test pilots to assess PIO tendencies and other handling qualities. The host aircraft has a safety pilot who can disengage the in-flight simulation mode and regain control of the aircraft using the primary flight control system of the host aircraft in the event of any danger. Thus the evaluation pilot is free to concentrate on the assessment tasks. The LCA control laws (both schedule and fixed gain versions) were extensively evaluated in two in-flight simulation campaigns using the USAF - CALSPAN In-flight simulators NT-33A (1995) and F-16 VISTA (1996).

Having thus thoroughly tested and verified the performance of the control laws these were transferred to the System House (ADE) for on-board implementation in the quad redundant digital flight control computer (DFCC).

To study hardware-in-loop effects on the performance of the control laws a complex 'Iron-Bird' facility has been set up at HAL. This facility has all the aircraft hardware elements related to the FCS including the FCC and pilot

cockpit interfaces. A full six degree of freedom nonlinear realtime simulation computer interface with single window visuals allows the pilot to perform comprehensive system level tests under normal and failure conditions over the entire flight envelope. This facility has been extensively used to test the overall FCS, and just prior to the first flight of LCA TD-1 the system integrity and reliability was established by conducting a "50 hour fault-free" test.

After extensive aircraft level ground tests where the FCS performance is verified using external electrical and hydraulic power with all other onboard systems operational, the FCS is evaluated in the autonomous mode during Engine Ground Run (EGR) tests where the stationary aircraft is tested with the engine operating at various thrust levels from ground idle to max. afterburner. This is followed by low speed and high-speed taxi trials on the runway to confirm satisfactory functioning of all systems under dynamic conditions.

The maiden flight of LCA TD-1 took place on 4th January 2001 and the aircraft has successfully completed the first block of twelve test flights. These flights were carried out basically to calibrate the airdata system and identify the aerodynamic stability and control characteristics. The pilots have rated the aircraft as level I in all tasks performed during these flights. The good match in the responses between flight and simulation has given the designers adequate confidence to expand the flight envelope in the subsequent flight tests to be carried out shortly.

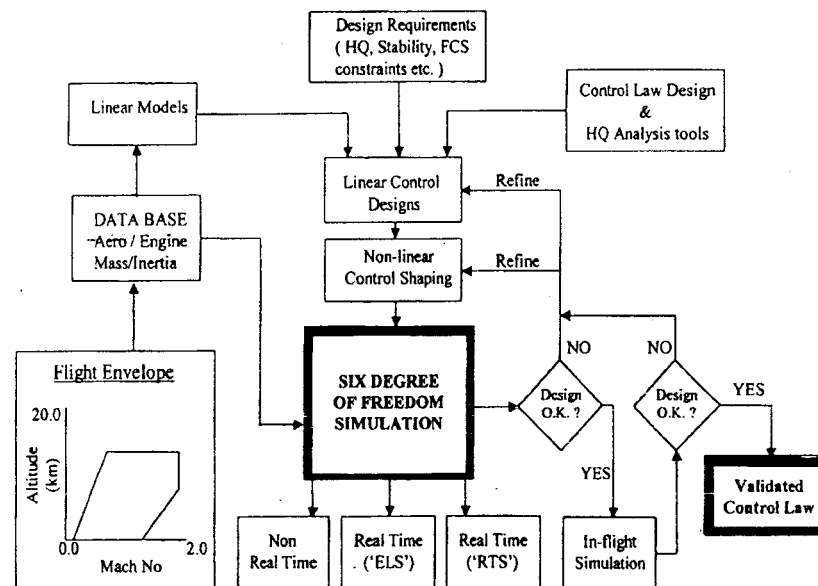


Fig. 1 LCA Control law synthesis cycle